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TERMINAL BALLISTICS OF CONCRETE-POLYMER SYSTEMS

Kenneth L. Moore, et al

Naval Weapons Center

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September 1975

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## TERMINAL BALLISTICS OF CONCRETE POLYMER SYSTEMS

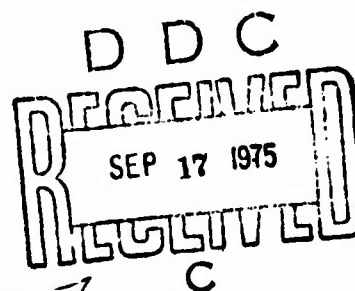
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The terminal ballistic properties of certain concrete-polymer systems have been evaluated. Penetration and cratering measurements were made on three different types of materials: (1) polymer concrete consisting of rock and sand bound by a cured polymer; (2) cured portland cement concrete into which liquid monomers were injected and then cured to varying degrees of polymerization; (3) latex modified concrete which differed from portland cement concrete only in the substitution of latex emulsion for portions of the mix water. Data obtained from impact of 0.30-caliber projectiles indicates that all three systems can (OVER)		

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ABSTRACT (Cont'd)

produce structural concrete with superior terminal ballistics behavior. Penetration was reduced by up to 30 percent, and cratering by up to 100 percent, with virtual elimination of cracking in the target material.

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## CONTENTS

Section	Page
I. Introduction	5
II. Damage Mechanisms in Concrete	7
III. Polymer Concrete	11
IV. Polymer-Impregnated Concrete	17
V. Latex-Modified Concrete	21
VI. Electron Microscope Studies	26
VII. Related Technology	32
VIII. Conclusions	34
Appendix	35

## ILLUSTRATIONS

Figure	Page
1. Damaged Regions in Concrete Targets	8
2. Typical Reinforcing Steel Lacing Pattern	9
3. Improved Lacing Pattern	10
4. USBR Polymer Concrete Sample	14
5. Diagram of Projectile Path Inside NWC PC Sample	15
6. Polymer Injection Apparatus	18
7. Cratering in Portland Cement Concrete	19
8. Effects of Butyl Acrylate on Cratering	20
9. Penetration of LMC Made with CE1-P	22
10. Cratering in Latex-Modified Concrete	24
11. Crater Volume Variation in LMC Targets	25
12. Crystal Growth in Portland Cement Concrete	27
13. Crystal Growth in Latex-Modified Concrete	28
14. Crystal Growth in Control Sample	28
15. Butyl Acrylate in Portland Cement Concrete	29
16. Methyl Acrylate in Portland Cement Concrete	30
17. Flexure Testing of Reinforced Concrete	33

## **TABLES**

<b>Table</b>	<b>Page</b>
1. Properties of USBR Polymer Concrete	12
2. Properties of NWC Styrene-Polyester Concrete	12
3. Characteristics of .30 Caliber M2AP Ammunition	13
4. Terminal Ballistic Data from Polymer Concrete	14
5. Comparison of Two Polymer Concretes	16
6. Composition of Polymer Impregnants	17
7. Terminal Ballistic Data from Polymer-Impregnated Concrete	19
8. Penetration and Cratering of LMC Targets	23



## SECTION I

### INTRODUCTION

Concrete-polymer systems have been evaluated at the Naval Weapons Center to determine their usefulness in upgrading existing military structures as well as for use in new construction. Previously, these materials had been investigated by the Bureau of Reclamation and by the Naval Civil Engineering Laboratory (see ref. 1, 2, and 3). This work was performed in an attempt to develop constructional materials with load-bearing properties similar to those of standard concrete, but possessing superior resistance to erosion and chemical attack.

The use of polymeric additives in these materials suggested the possibility of their use in fortifications as a means of reducing penetration by high velocity projectiles. A second but equally important application would be for the control of cratering and cracking due to projectile impact. The test program called for the acquisition of adequately sized targets fabricated from the materials selected. At the time, budget restrictions and **chemical** shortages led to the fabrication of relatively small targets into which .30 caliber armor piercing projectiles were fired.

Three different types of material were selected for the impact tests. The first was polymer concrete (PC), also known as polymer-bound aggregate (PBA), consisting of rock, sand, and a polymer binder. Certain chemicals were added in an attempt to modify the glass-like properties of the polymer under conditions of low temperature and high loading rate. The second material was cured portland-cement concrete into which liquid monomers were injected under pressure, with subsequent in-situ polymerization; this is known as polymer-impregnated concrete (PIC). The final material investigated was latex-modified concrete (LMC) which differed from portland cement concrete only in the substitution of latex emulsions for part of the mix water.

- 
1. Concrete-Polymer Materials, First through Fifth Topical Reports, Bureau of Reclamation, Denver, Colorado.
  2. Keeton, J. R., et al., Concrete-Polymer Composite for Military Underseas Facilities, Naval Civil Engineering Laboratory, Point Mugu, TN-1230, April 1972.
  3. Keeton, J. R., et al., Polymer-Strengthened Concrete for Military Facilities, NCEL TN-1319, December 1973.

From the outset it was realized that the behavior of the target materials would depend on such factors as degree of polymerization and cross-linking, the presence of bonding agents to provide a modulus of elasticity intermediate to those of the aggregate and the polymer, and the high-rate loading properties of the bulk polymer itself. Laboratory tests conducted on all of the systems indicated that it would be possible to devise mix procedures which could be used in preparing bulk targets with the desired properties. At the same time, however, it was realized that any material ultimately selected for use would be subject to the dual requirements of low cost and ease of preparation and handling by construction personnel.

Test results indicate that all three of the systems tested can produce concrete with superior penetration resistance as well as improved resistance to cratering and crack propagation. The operational fabrication procedures were found to be important, but not critical within wide ranges of polymer concentration and degree of polymerization.

## SECTION II

### DAMAGE MECHANISMS IN CONCRETE

Previous measurements of ballistic penetration of concrete indicated a possible inverse relationship between static compressive strength and penetration depth. While this relation may hold for "infinite" or massive targets, a much greater influence on penetration and bulk damage is exerted by the concrete tensile strength. This is especially true for thin targets and for hits near the target edge or adjacent to a crater resulting from a previous impact. The tensile strength of standard concrete is very low, usually on the order of 300 psi, which is less than the strength of most rocks used as aggregates in concrete. Consequently the greater portion of bulk damage in concrete is due to tensile stresses resulting from acoustic mismatches at binder-aggregate and target-air interfaces.

When a projectile strikes a concrete target the following sequence of events occurs:

1. The force of the impact initiates a compressive stress wave in the concrete. The amplitude of the wave is a function of projectile energy and nose radius as well as the rate at which projectile velocity is reduced. That is, a projectile brought to rest in a few microseconds will induce greater stresses than one stopping after a millisecond of gradual deceleration.

2. The compressive wave propagates spherically into the target, diminishing in amplitude as the second power of the distance from point of impact. As the wave encounters aggregate material, with modulus higher than that of the matrix cement, it experiences an acoustic impedance mismatch. That is, a portion of the wave propagates into the higher modulus material stressing it in compression, while the remainder reflects back into the cement stressing it in compression. The resultant dynamic force is a tensile stress at the cement-aggregate interface. For points close to the impact the compressive wave has sufficient intensity to crush the cement and break it directly in compression. At greater distances the amplitude is so reduced that induced tensile stresses become the dominant fracture mechanism.

3. Simultaneous to the events in item 2, a compressive wave propagates radially outward on the target surface; its amplitude is reduced as the first power of the distance from the point of impact. Due either to accident or design, cured bulk concrete often has a smooth outer layer fairly free of large aggregate. As a result of these two factors bulk damage normally is experienced farther from the impact point along the surface than along the

penetration path (see Figure 1). The crater resulting from a projectile impact is normally shallow in relation to its width, with aspect ratios (crater diameter divided by crater depth) ranging from 3 to 8.

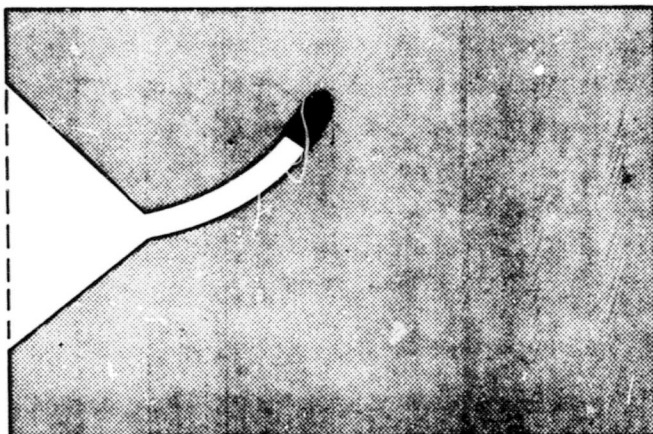


Figure 1. Damaged Regions in Concrete Targets. A typical impact in concrete. Crater diameter usually exceeds crater depth, resulting in the generation of free surfaces which reduce target resistance to multiple-hit attacks.

4. When the bulk acoustic wave encounters a free surface, it reflects and again induces tensile stresses, this time inside the body of the target. The result is massive cracking and breakage which often causes greater structural damage than the initial impact and crater. The presence of steel reinforcing rod inside the concrete can actually aid the breakage process, as a severe impedance mismatch occurs at the cement-steel interface. In addition, the geometric pattern of the steel reduces the concrete penetration resistance in planes formed by parallel rods. Figure 2 illustrates this effect; Figure 3 shows a preferable arrangement (see ref. 4).

5. Projectiles impacting at velocities greater than the speed of sound in the target will precede the resultant compressive stress waves. It is possible for such a projectile to be brought to rest inside the target before the stress waves can break up the back face of the target, whereas a slower projectile might find crack paths opening up ahead of it as a result of back face breakage.

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4. Effects of Impact and Explosion, Vol. I, 1946. Available from NTIS, Arlington, Virginia.

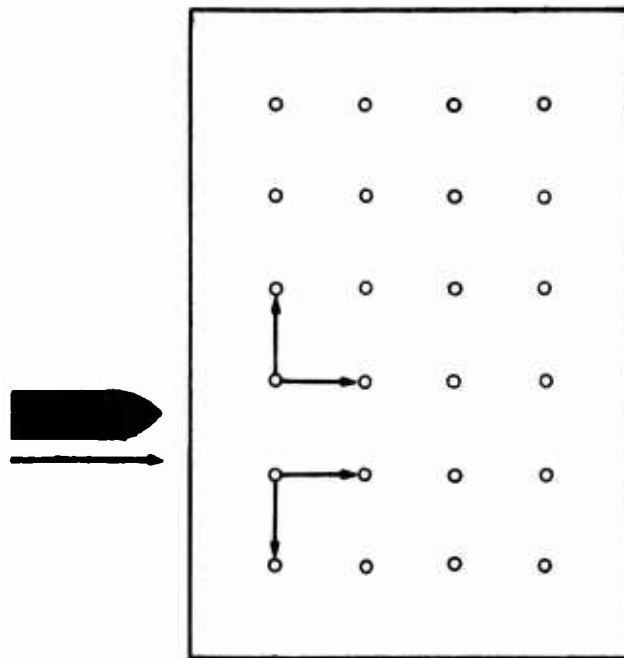
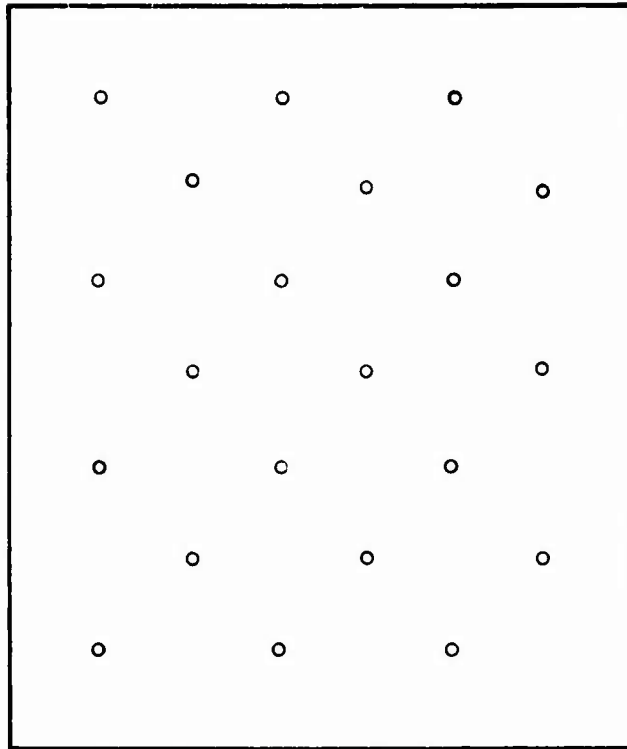


Figure 2. Typical Reinforcing Steel Lacing Pattern. Reinforcing steel is normally laced in a cubic lattice with its members forming planes parallel to the free surfaces. These planes reduce target resistance to impacts perpendicular to the free surfaces by providing a series of impedance mismatch nodes for stress waves propagating through the target. Major cracks will form and propagate along nearest-neighbor planes. The arrows indicate directional preference of breakage.

In the search for suitable polymer binders a number of conclusions were drawn from the phenomena just described. Foremost among these are the dynamic properties of the binder itself: the impedance (density-velocity product) of the binder must match the aggregate impedance as closely as possible; a coupling agent is desirable if such impedance matching cannot be achieved; it will be highly desirable to have the binder flow slightly at high loading rates, rather than behaving as a glass-like brittle material. In addition, the velocity of sound should be as low as possible if such is commensurate with desired structural properties. The binder should form a continuous phase throughout the target rather than consisting of a paste-like mixture of variously-sized particles.

Samples of polymer concrete, polymer-impregnated concrete, and latex-modified concrete were prepared for the purpose of testing the above-mentioned hypothesis. Target data and test results are contained in Sections III, IV, and V.



**Figure 3. Improved Lacing Pattern. An improved lacing pattern for reinforcing steel. It is possible to use the same amount of steel and obtain the same structural properties as with a cubic lattice, while reducing cracking along preferential planes, by offsetting alternate rows by one-half of a lattice spacing. This should be done in both vertical and horizontal planes.**

### SECTION III

#### POLYMER CONCRETE

Polymer concrete (PC), as mentioned previously, consists of sand, rock, and a suitably prepared and cured polymer binder. No water is used in PC, and portland cement is used only as a source of "pan" material, that is, material passing through a number 200 standard sieve.

PC has been investigated extensively by the United States Bureau of Reclamation (USBR), Department of the Interior. In a series of annual reports (ref. 1), USBR researchers have noted the effects on compression strength of binder material and modulus, coupling agents, and gradation of fine particulates in the sand portion of the mix.

A sample of PC was obtained from USBR in the form of a one-foot cube. The PC had a compressive strength in excess of 18,000 psi and tensile strength of 1,500 psi. The constituents and properties of the PC sample are given in Table 1. Since cured poly (methyl methacrylate) is somewhat brittle (due to its relatively high glass transition temperature ( $T_g$ )), another monomer, trimethanolpropane trimethacrylate (TMPTMA), was introduced in the amount of 2.5% in an attempt to improve impact resistance. Silane coupling agent at 0.5% was intended to form an elastic bond between the high-modulus aggregate and the low-modulus binder (see ref. 5 and 6). Benzoyl peroxide (BP) and dimethyl aniline (DMA) are used to initiate a free-radical curing process, with the benzoyl peroxide being dissolved in the monomer prior to mix; the dimethyl aniline is added immediately before pouring the monomer into the cement mixer.

The second PC sample was fabricated at NWC using styrene-polyester boat resin (ref. 7) as the binder. The aggregate consisted of sand and gravel supplied by the Public Works Department. Catalysis was achieved by adding 1% hydrogen peroxide to the liquid prior to mix. Actual mixing was performed in a one-gallon paint can mounted on a vibrating paint shaker. Cure time was approximately two hours. The resultant concrete was somewhat soft due to an incomplete cure, but was tested as a possible candidate for overlays on existing structures as well as for emergency repairs on concrete and asphalt runways. Properties of the styrene-polyester PC are given in Table 2.

5. von Plueddemann, Edwin, Zwitterion Silane-Modified Polymer Latices. Dow Corning Corporation, May 24, 1973.
6. "Silane Coupling Agents", Dow Corning Chemical Corporation, Midland, Michigan, 1970.
7. Beckman, H. J., Ashland Chemical Company. Private communication.

Table 1.

## Properties of USBR Polymer Concrete

Aggregate		Monomer system	Weight, g
Sieve size	Weight, lb		
Pan	24.8	Methyl methacrylate	5797.4
-50 + 100	9.4	TMPTMA	148.7
-30 + 50	14.3	Benzoyl peroxide	59.5
-16 + 30	14.8	Dimethyl analine	29.7
- 8 + 16	8.0	A-110 silane	29.7
3/8 + -8	8.9		
4 to 3/8	32.2		
3/8 to 3/4	48.3		
Compressive strength, psi			18,300.0
Tensile strength, psi			1,500.0
Density, lb/ft <sup>3</sup>			150.0

Table 2.

## Properties of Styrene-Polyester Concrete

Aggregate*		Binder**	
Item	Weight, lb	Item	Weight, g
Rock	8.6	Resin	1125
Sand	5.8	Hydrogen peroxide	11
Compressive strength, psi			1000
Tensile strength, psi			350

\* Rock and sand supplied by NWC Public Works Department.

\*\* WEP 661P, Ashland Chemical Company.



Original plans called for 20 and 40 mm projectiles to be used in evaluating the performance of PC. However, the extremely high compressive strength of the USBR sample would have necessitated an inordinately long cure time for encapsulating concrete if an acceptable impedance match were to be obtained. For this reason .30 caliber M2 armor-piercing ammunition was used in the impact tests. Details of the AP projectiles are given in Table 3. Terminal ballistic performance of both PC samples were in general agreement with results expected from the foregoing discussion.

Table 3.  
Armor Piercing Projectile, Caliber .30 M2

Round: .30 - 06	Hardened steel penetrator
Load: 55 grains IMR 4895	
Projectile weight, grains	155
Penetrator weight, grains	77
Penetrator diameter, mm	6.2

The USBR sample brought the projectile to a halt at a penetration depth of 1.7 inches, measured from front surface to nose of projectile. Crater volume was 140 cc, crater depth 0.9 inches, and mean crater diameter 6 inches (see Figure 4). By comparison (see Table 4), a control sample of 6,000 psi portland cement concrete was penetrated 2.6 inches (Figure 5). The PC sample thus experienced a penetration reduction of 35% compared to the control. However, the force of the impact created two radial cracks extending to the edges of the front surface, and, in addition, opened up several invisible cracks inside the body of the target. The magnitude of these channels became apparent during measurements of crater volume, when the block was observed to leak water in several places less than one second after the water was poured into the crater. Satisfactory measurements of crater volume were obtained only after the crater surface was coated with an acrylic spray to seal the cracks.

The styrene-polyester concrete was penetrated to a depth of 4.0 inches. The irregular front surface prevented accurate determination of crater dimensions, which are given as estimates in Table 4. The interesting features of this sample were that the penetrator broke at the point of maximum penetration, and that the penetrator turned back toward the front surface, travelling about one inch before coming to rest. This is diagrammed in Figure 5.

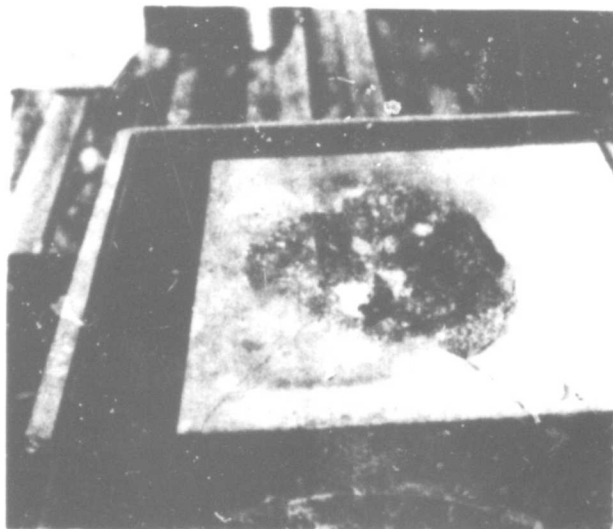


Figure 4. USBR Polymer Concrete Sample. Post-impact photograph showing cratering and cracking caused by .30 M2 armor-piercing round at 2,850 feet per second. Original sample was a cube measuring one foot on an edge. The radial cracks were caused by brittle fracture of the poly (methyl methacrylate) binder, impacted below its glass transition temperature.

Table 4.  
A Comparison of Impact Data from Polymer  
Concrete with Control Concrete\*

Parameter	USBR	NWC	Control
Penetration, inches**	1.7	4.0	2.6
Crater diameter, inches	6.0	1.5	4.2
Crater depth, inches	0.9	0.8	1.2
Crater volume, cc	140.0	8.0	90.0

\* 4000 psi concrete foundation block.

\*\* Measured to nose of penetrator, or to point of deepest penetration, whichever is greater.

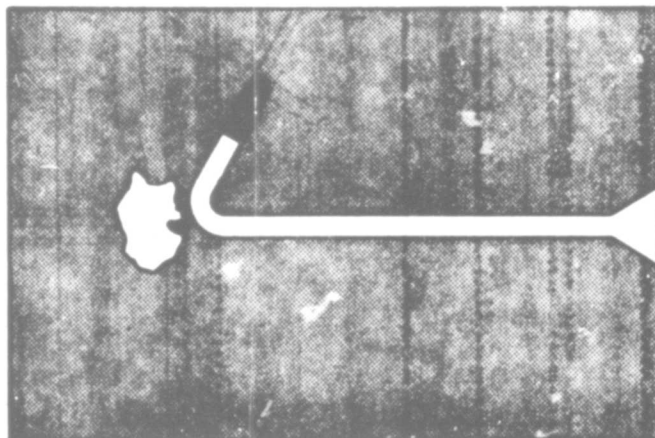


Figure 5. Diagram of Projectile Path Inside NWC Polymer Concrete Sample. The penetrator rebounded from the rock shown, broke in half, and turned back toward the front surface. The rock, approximately 0.5 inch in diameter, was scratched but not broken by the impact.

The behavior of the USBR poly (methyl methacrylate) concrete is due to the fact that the binder material, below its glass transition temperature, is extremely brittle under impact. The high loading rate elastic and rheological properties of the acrylates and methacrylates are not well understood at this time.

Styrene-polyester resins are formulated as binders for fiberglass in such applications as boat hull construction, and consequently must exhibit some degree of post-cure flexibility. The particular sample used in the ballistic tests was cured to a semi-rigid state in the hope that such a matrix would not suffer the bulk damage normally induced in concrete. Whereas a piece of normal concrete the same size would have broken into a large number of small fragments, the PC sample retained its integrity and had to be broken apart before the projectile could be located. For ease of preparation, mixing, and casting, concrete prepared with a styrene-polyester binder appears much superior to PMMA concrete, which must be covered for several hours to prevent binder loss through evaporation. The cost of the styrene-polyester resin is much lower than that of the chemicals required for producing a methyl methacrylate concrete. A comparison of PMMA concrete and styrene-polyester concrete

is given in Table 5. In summary, styrene-polyester concrete seems to be a good candidate material for larger-caliber projectile tests. Its ability to defeat projectiles while retaining structural integrity indicate potential applications as overlay material as well as for new construction in targets which might expect multiple-hit-attacks.

Table 5.  
Comparison of Two Polymer Concretes

	USBR (PMMA)	NWC (styrene/polyester)
Compressive strength, psi	18,000 - 24,000	1,000 - 6,000
Tensile strength, psi	1,500 - 1,800	300 - 4,000
Density, lb/ft <sup>3</sup>	150	160
Pounds of binder per cubic yard	243	490
Cost of binder per cubic yard, \$	120	50

## SECTION IV

### POLYMER-IMPREGNATED CONCRETE

Polymer-impregnated concrete (PIC) was investigated by USBR as a means of improving static properties of existing concrete structures, and of reducing the vulnerability of such structures to erosion and chemical attack. Specific impregnants used at USBR include methyl methacrylate (MMA), styrene, acrylonitrile, and polyester resins. With the exception of styrene, all systems tested improved the compressive and tensile strength of concrete by 100 to 350 percent using the free-radical cure. This data is found in ref. 1.

For the NWC program four systems were selected. These were methyl acrylate (MA), butyl acrylate (BA), MMA, and MMA + 30% BA. One liter of each monomer was prepared (Table 6) and injected into a monolithic block of concrete measuring 2 feet square by 4 feet long. A hydraulic ram (Figure 6) was mounted on the concrete and used to inject monomers into the block under pressure. Since the catalyst and promoter had been added to the monomer prior to injection, it became necessary to use injection pressures of 60 to 100 psi to ensure impregnation. Otherwise the polymerization process would increase the chain lengths to the point that the fluid would no longer penetrate the pores in the concrete.

Table 6.

Composition of Polymer Impregnants

Component	System			
	MMA	MMA/BA	MA	BA
Binder volume, cc	MMA 1000	MMA 700	MA 1000	BA 1000
Plasticizer volume, cc	TMPTMA 25	BA 200	...	...
Coupling agent weight, g	A-1100 10	A-1100 10	A-1100 10	A-1100 10
Catalyst weight, g	BP 12	BP 12	BP 12	BP 12
Accelerator weight, g	DMA 12	DMA 12	DMA 12	DMA 12

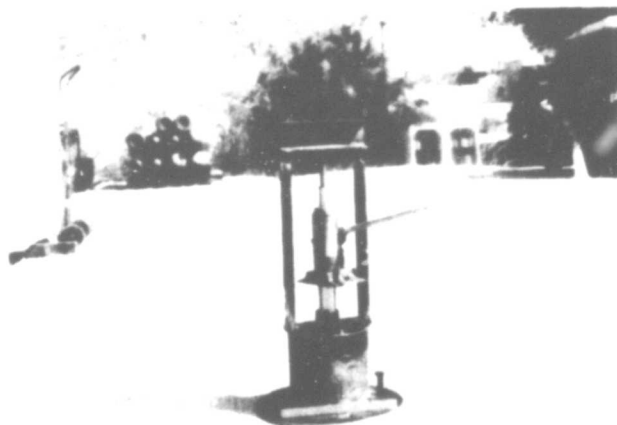


Figure 6. Polymer Injection Apparatus. The cylinder is attached to the concrete with epoxy, which also serves as a seal against monomer leakage. Machine screws (one shown) are used in removal of the apparatus from the concrete.

Armor-piercing projectiles, caliber .30 M2, were fired into each of the four impregnated areas as well as into an untreated portion of the block. Test results are given in Table 7. The changes in penetration are not felt to be conclusive or even indicative of the potential of impregnation of concrete fortifications. The actual penetration depths vary less than a series of similar shots into untreated concrete. This indicates that injected polymeric material may tend to make concrete a more consistent material for defeating incoming projectiles.

The section modified with butyl acrylate showed the greatest deviation from standard concrete, with a reduction in crater volume of over 68% (see Figures 7 and 8). The aspect ratio of the crater decreased to less than one, the first definite instance of this noted in the tests. The butyl acrylate penetrated to a depth of at least 2.5 inches and cured to a rubbery state as predicted. The presence of butyl acrylate served to attenuate shock wave propagation as well as to hold the concrete together in places where cracks did occur. Pieces of concrete were broken off in an attempt to determine the extent of polymer penetration; it was noted that both cement and rock had been permeated by the liquid, which subsequently cured to form a continuous phase inside the concrete.

Table 7.  
Terminal Ballistic Data from PIC Targets

	Monomer system				
	MMA	MMA/BA	MA	BA	Control
Penetration, inches	2.7	3.0	2.7	3.0	2.9
Crater diameter, inches	3.2	4.5	4.8	2.9	4.2
Crater depth, inches	1.0	1.0	1.0	1.1	1.0
Crater volume, cc	44	87	99	24	76

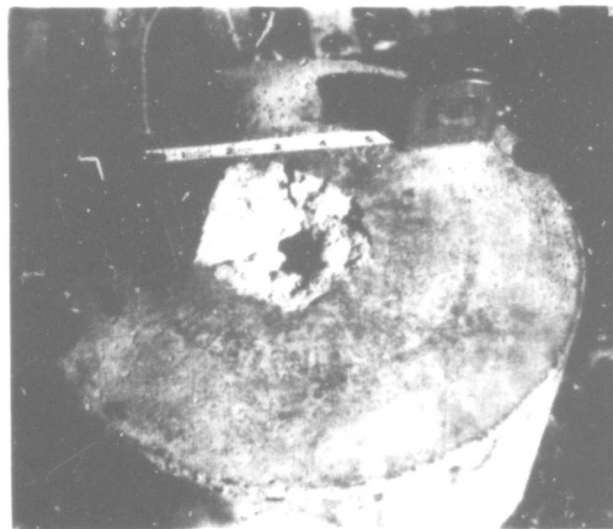


Figure 7. Cratering in Portland Cement Concrete. Projectile impacts in concrete normally cause a crater to be formed. The diameter of this crater is typically three to eight times the crater depth, as measured from the original free surface to the bottom of the sloping walls.

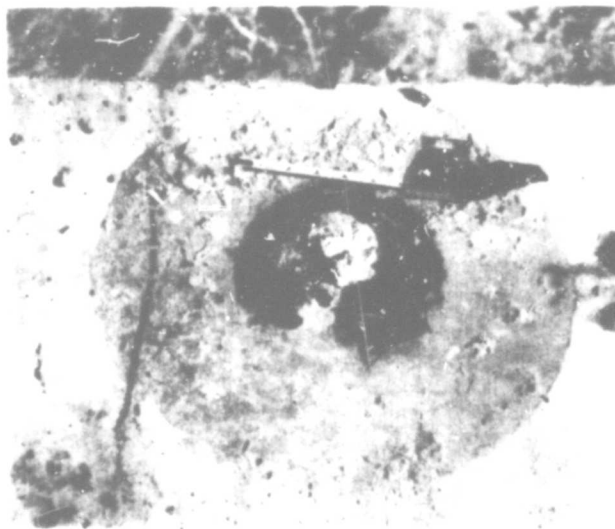


Figure 8. Effects of Butyl Acrylate on Cratering. This photograph illustrates the change in crater aspect ratio (diameter divided by depth) when a rubbery polymer with low glass transition temperature is injected into cured portland cement concrete.

It is possible that other of the acrylates and methacrylates could be cured to similar conditions; among the more promising are hydroxy propyl acrylate and ethyl acrylate. At the present time, however, butyl acrylate has been demonstrated as effective in reducing cratering, and seems an ideal candidate for use in upgrading existing structures where multiple hits are to be expected.



## SECTION V

### LATEX MODIFIED CONCRETE

Latex-modified concrete (LMC) is a variant of standard portland cement concrete in which a water emulsion of polymer latex is substituted for a portion of the mix water. LMC additives have been developed by several manufacturers for use in concrete and plaster fabrication where standard concrete has marginal utility. Among the benefits to be gained from the use of such additives are improved freeze-thaw resistance, decrease in crack propagation, greater flexibility, and increased resistance to impacts such as hammer blows or falling objects. This latter property suggested application as an overlay on existing structures as well as for use in new military construction. NCEL, Point Hueneme, has investigated a number of such latices for use in undersea construction (ref. 2 and 3), and the Soviets have considered LMC for use in large structures (ref. 8).

Most commercially available latex emulsions contain approximately 50% solids in the form of micron- or submicron-size particles. Latices of interest include homopolymers of ethylene, vinyl chloride, and styrene, copolymers such as vinyl chloride-vinyl alcohol, and terpolymers of which vinyl chloride-vinyl alcohol-vinyl acetate is one example. In concrete usage the emulsions are diluted 1:1 with water. This brings the polymer content of the product to 7 to 10% of the weight of portland cement, which is the optimum quantity as determined empirically. One notable feature of the latices is their lubricating property; the use of latex emulsions increases the fluidity of the concrete mix and permits the builder to use no more water than that required for chemical set of the cement. This results in much shorter cure times; full-strength cure of type II portland cement has been noted in as little as three days. In addition, the presence of polymer additives helps to seal the outer surface against water loss by evaporation. This can be of definite value in desert or arctic construction.

Four different latices were used in the preparation of LMC targets. These were CE 1-P, A-400, A-401, and A-420, all manufactured by Air Products and Chemical Corporation. Numerous other latex emulsions have been formulated; known examples are listed in the Appendix. CE 1-P is a modified vinyl acetate homopolymer emulsion formulated especially as a bonding agent and fortifying admixture for concrete; A-400 is an emulsion of vinyl-ethylene copolymer. A-401 and A-420 are ethylene-vinyl acetate copolymers.

8. Vaitkyavichius, V. I. and Kudzys, A. On the Cracking Resistance of Polymer Cement Concrete Beams. Translated from Russian and published by USAFSC as FTD-MC-23-1960-74.

For the purposes of standardizing the tests and reducing costs, concrete targets were cast using sacked ready-mix concrete. The general formula was 85 pounds of ready-mix plus the desired amounts of water and latex to vary the polymer content from 0 to 12%. At polymer concentrations of 6, 9, and 12%, additional samples were prepared which contained the same amount of water as the control sample. The only series of targets to show a systematic variation in penetration depth was that made with CE 1-P, which was the only additive formulated specifically for use in concrete. This variation is plotted in Figure 9; data on all targets is found in Table 8.

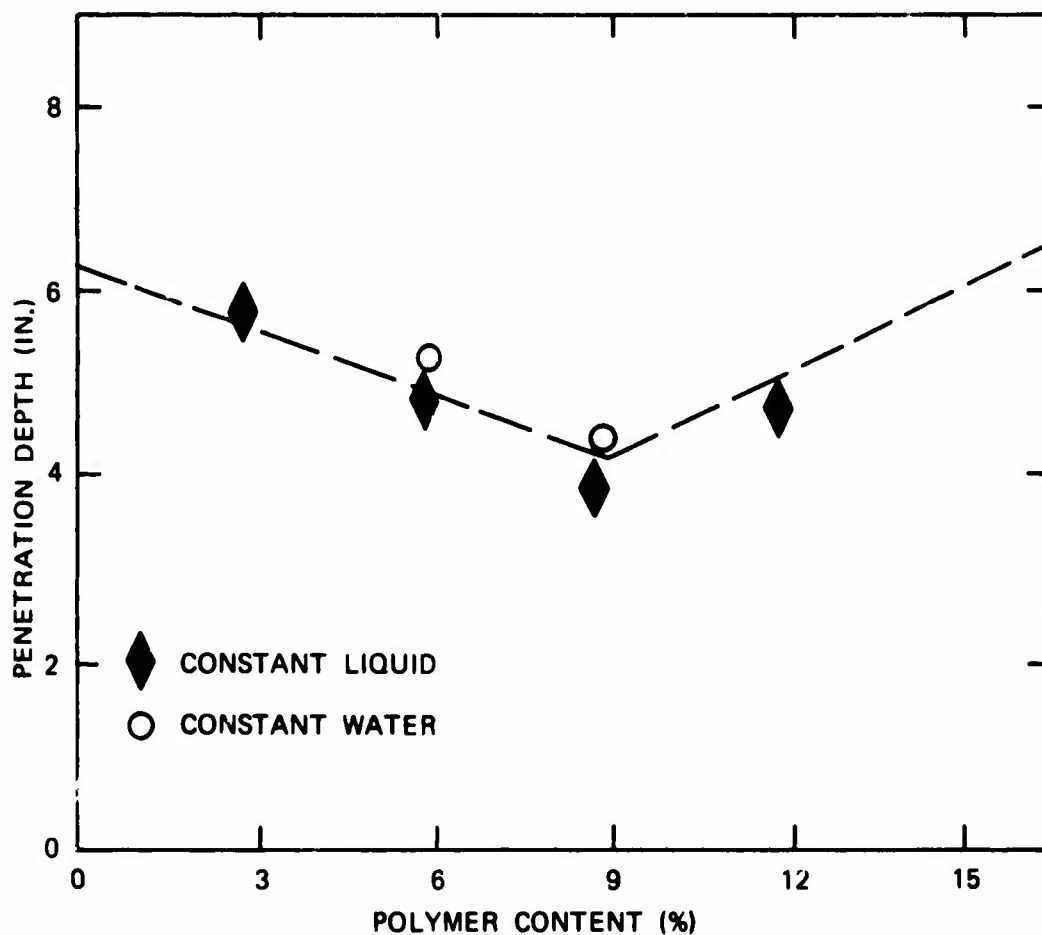


Figure 9. Penetration of LMC Made With CE1-P. This series of samples exhibited a reduction in penetration which reached a maximum at 9% polymer, relative to portland cement content. Penetration reduction at this concentration was approximately 32%.

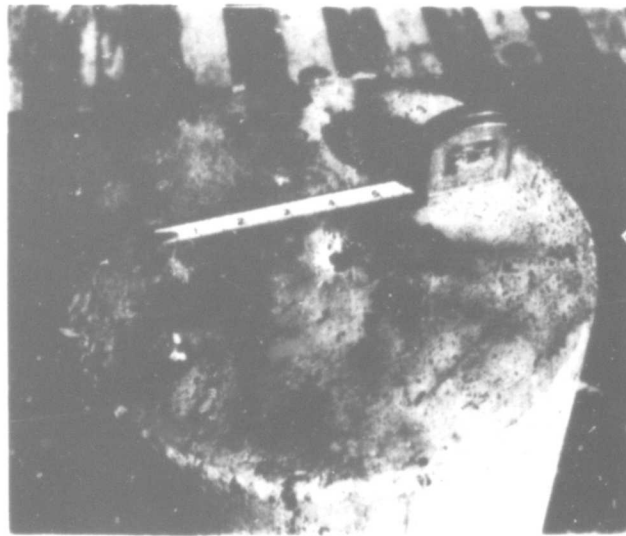
**Table 8.**  
**Penetration and Cratering of LMC Targets**

Sample and % polymer	Penetration, in.	Crater volume, cc	Compressive strength, psi
CE 1-P 3	5.7	25	1780
6	4.9	14	1730
9	4.1	12	2200
12	4.9	35	4080
A-400 3	4.0	27	4780
6	7.0	8	1900
9	6.5	0	2150
12	6.5	46	2200
A-401 3	5.7	26	3350
6	5.5	6	1600
9	5.5	7	1500
12	7.7	14	1810
A-420 3	6.5	30	1600
6	5.1	6	1850
9	6.5	8	2700
12	7.0	12	1900
Control* 0	6.2	130	3200

\* Average value based on four samples.

The most interesting result of the LMC tests was the discovery that cratering and cracking are reduced by up to 100% (Figure 10); the patterns were similar for all four latices. The data is found in Table 8, and presented in graphic form in Figure 11. Compressive strengths, listed in Table 8, are very irregular; there is no apparent relationship between compressive strength and either depth of penetration or crater volume.

Crater reduction in LMC is apparently achieved by the same mechanism as in PIC. That is, the latex globules coalesce as water is taken up by hydration of the portland cement, and form a continuous film of tough, flexible polymer throughout the concrete. This film acts as an attenuator for shock waves and, by chemical as well as physical attachment to cement and aggregate, helps hold the concrete together when it is loaded in tension. According to manufacturers' claims, static tensile strength is typically increased by 300%, although this was not observed. Similar increases are apparently obtained at the high loading rates associated with projectile impacts.



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Figure 10. Cratering in Latex-Modified Concrete. The inclusion of 7 to 10% latex emulsion (relative to portland cement content) in a concrete mix results in significant reductions in crater volume and crack damage. This photograph shows a sample prepared with approximately 9% of Airflex A-400.

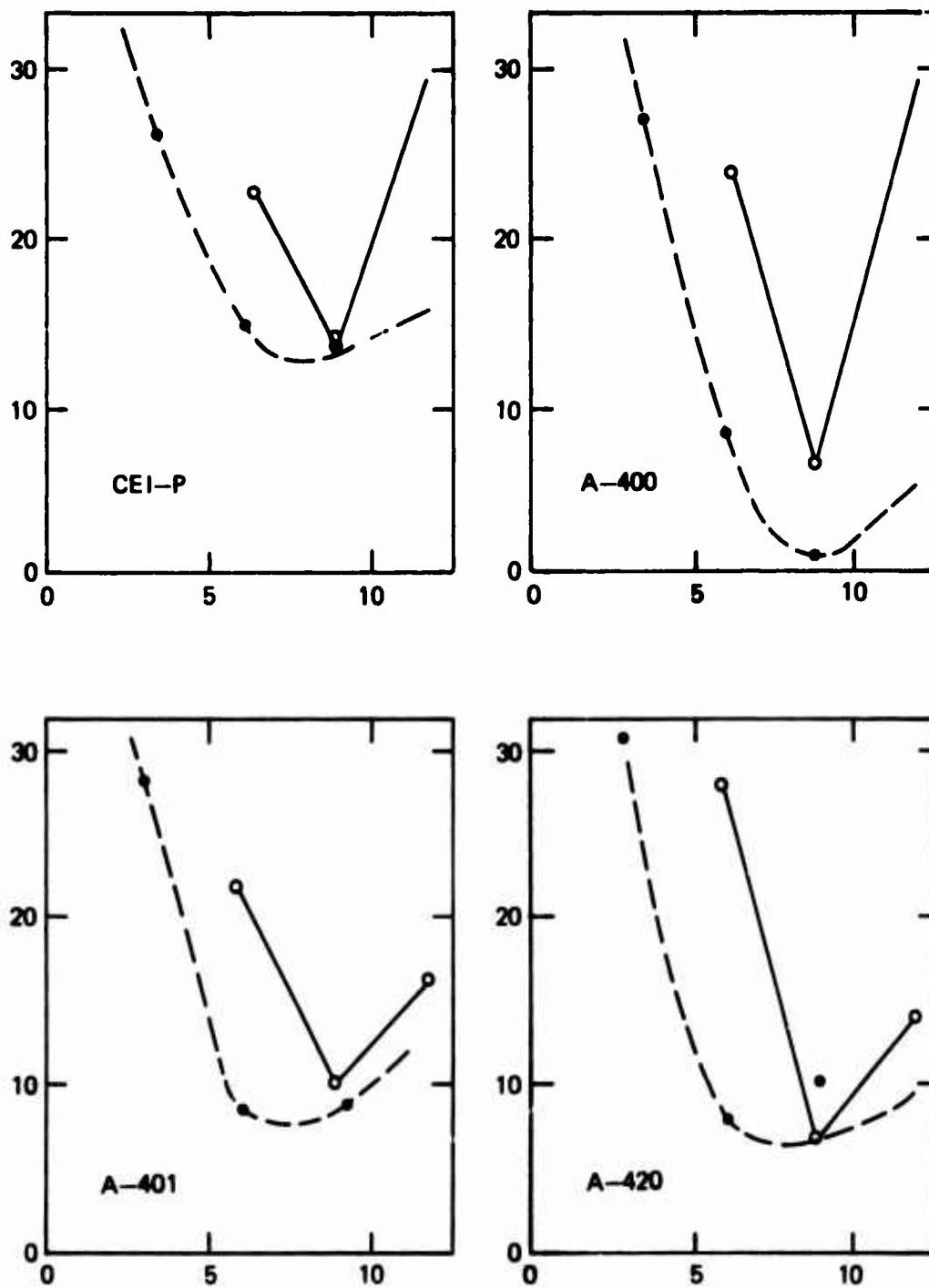


Figure 11. Crater Volume Variation in LMC Targets. Variation in crater volume with polymer content for four latex additives. Vertical axis (all graphs): crater volume in  $\text{cm}^3$ . Horizontal axis (all graphs): polymer content as percent of portland cement content.

## SECTION VI

### ELECTRON MICROSCOPE STUDIES

Samples taken from various concrete-polymer systems have been examined with the scanning electron microscope (SEM). The purpose of this investigation was to identify the polymer inside the cured concrete and to determine whether polymer and concrete micro-structures could be related to bulk phenomena. Specific phenomena sought were physical shape of polymer material, extent of penetration into concrete, and methods by which the polymer had become attached to the cement and aggregate.

Samples were taken from freshly broken surfaces in each of the targets, from cured concrete of known age and compressive strength, and from test tube samples with extremely high polymer concentration. The pieces selected for SEM use were given a 50 Angstrom thick coating of gold to prevent excessive charge buildup.

The cure process in portland cement concrete takes place as the cement takes up water of hydration. This is often accompanied by the growth of long, slender crystals (Figure 12), which are responsible for the increase in compressive strength as the cure progresses. They are also responsible for the tendency toward brittle fracture of cured concrete under impulsive loadings such as projectile impact.

Use of the SEM revealed that crystal growth in the latex-modified concrete (Figure 13) was apparently inhibited in comparison to similar growths in the untreated control samples (Figure 14). This growth inhibition is believed due either to the physical presence of the polymer material, acting as a restriction on crystal growth, or to a reduction in cement alkalinity caused perhaps by acidic behavior of the latex surface. While a definite conclusion has not been reached, it is apparent that the presence of latices can be used to control growth of calcium silicate hydrates, thus preventing brittle behavior in cured concrete.

Examination of polymer-impregnated concrete targets (Figures 15 and 16) confirmed visual observations concerning the role of impregnants in crack and crater reduction. In Figure 15 the butyl acrylate is seen adhering tenaciously to the hardened cement paste, and permeating the gel pores and capillaries. In Figure 16 the methyl acrylate, which cured to a hard, brittle condition, is seen to have fractured and exposed a number of smooth surfaces similar to those observed in freshly broken glass (Figure 16a, b). Deeper inside the cement, however, the methyl acrylate was undisturbed and permeated the gel thoroughly. Figures 16c and 16d show this, with a structure very similar to that of fused silica or blown glass.

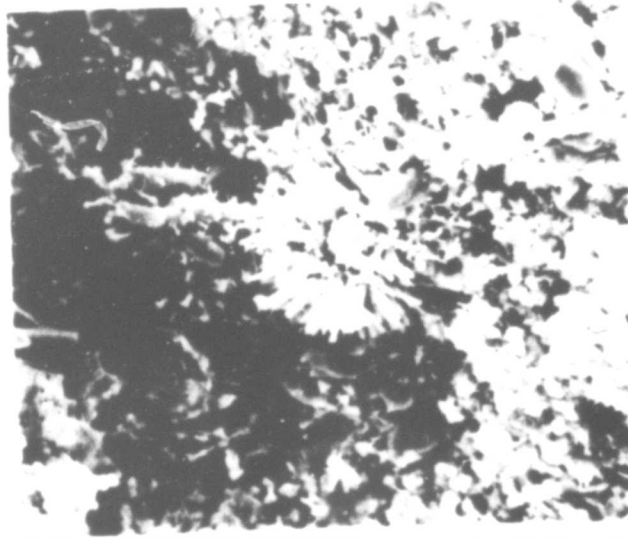


Figure 12. Crystal Growth in Portland Cement Concrete. The crystals form as calcium aluminate and calcium silicate take up water of hydration and precipitate out of the cement gel. The growth of these crystals is responsible for the increase in strength as the concrete cures, but also contributes to brittle behavior under projectile impacts. (2400X)



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Figure 13. Crystal Growth in Latex-Modified Concrete. The presence of latex material inhibits the growth of crystal structures. This is due to the reduction in cement alkalinity by residual acid in the latex. (2180X)

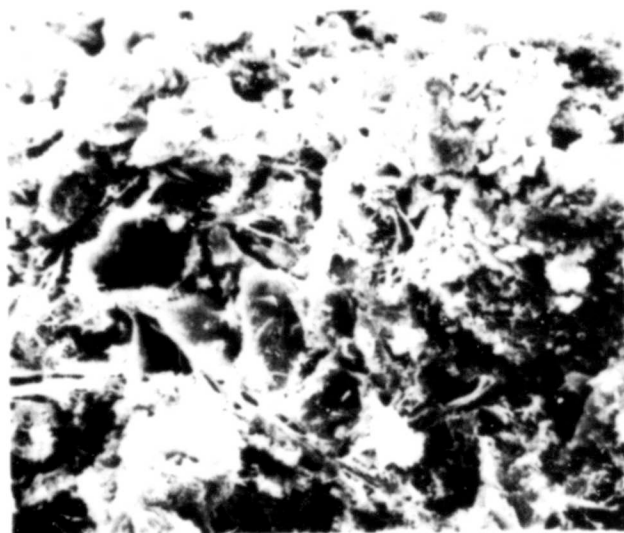


Figure 14. Crystal Growth in Control Sample. The control sample consisted of ready-mix concrete, identical to that used in the LMC samples. (2250X)

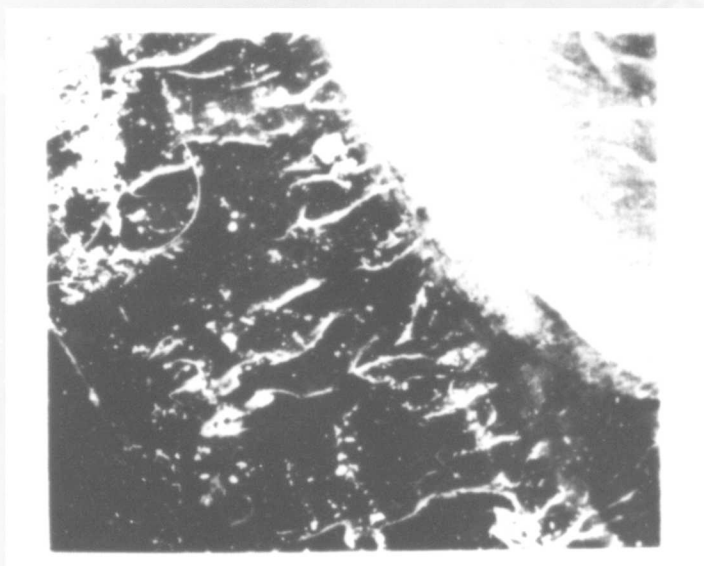




Figure 15. Butyl Acrylate in Portland Cement Concrete. The butyl acrylate (black material at left), injected into cured concrete at approximately 80 psi, has permeated the cement pores and capillaries before curing to a soft rubber-like material. This injection reduced cratering by 68% by attenuating the stress waves caused by projectile impact. It is important to note, in this regard, that butyl acrylate will penetrate rock as well, thus acting as an impedance-matching mechanism in cured concrete. (200X)

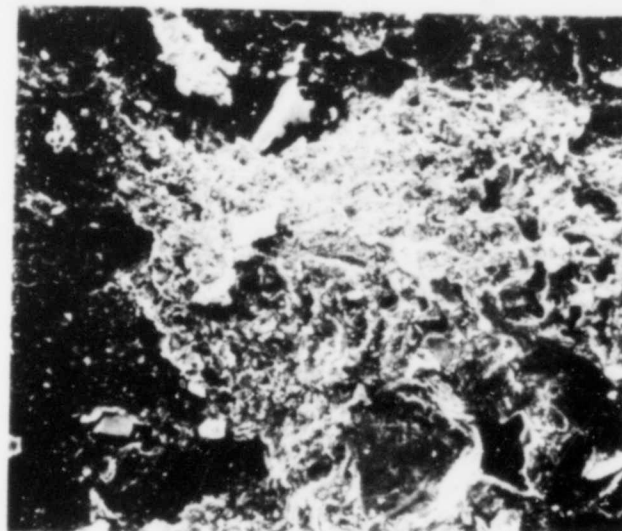


(a)

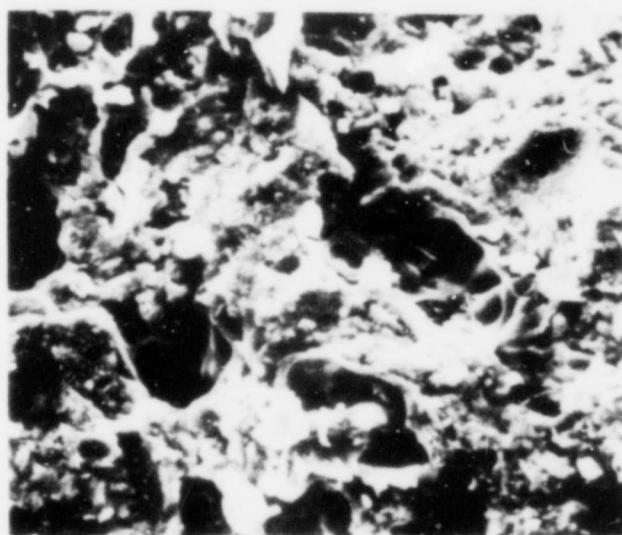


(b)

Figure 16. Methyl Acrylate in Portland Cement Concrete. (a) shows a fractured surface (20X) near the point of impact. (b) (500X) illustrates the brittle fracture experienced at this point. (c) (500X) shows polymer (light material) deeper inside the concrete. (d) (200X) is a close-up of the unbroken poly (methyl acrylate) showing it to have a structure much like that of fused silica.



(c)



(d)

Figure 16. (Continued)

## SECTION VII

### RELATED TECHNOLOGY

The original objective of concrete-polymer research at NWC was to establish methods and materials useful in military construction for defense against high-velocity projectiles. As the investigations progressed situations arose which indicated a number of alternate applications for such materials, in civilian as well as military activities.

The first potential application came in the field of earthquake engineering. A large number of California structures do not conform to existing earthquake codes and might face possible demolition under new, proposed building codes. Fundamental to the problem of earthquake vulnerability is the fact that a severe mismatch exists between the elastic properties of steel and of cured concrete. A seismic disturbance passing through a concrete structure induces oscillatory motion in the vertical members. The amplitude of these oscillations, combined with the differences in elastic properties, is sufficient to cause separation of concrete from reinforcing steel. After three or four complete cycles of sufficient amplitude the concrete will begin to separate from the steel, leading to structural collapse of the building. Contributing to the problem is the low tensile strength of concrete. This results in concrete breakage in horizontal members which is especially serious in floors and facade structures.

Two possible solutions to the problem were investigated at NWC. The first, intended for use in existing structures, involved injection of butyl acrylate and silane coupling agent into a cylinder of prestressed concrete (see Figure 17). A similar sample was used as a control in a flexure experiment. The experiment consisted in flexing the cylinder until cracks appeared in the concrete. At this point the concrete was broken loose from the steel bar to determine the extent of separation. The impregnated sample, which underwent a larger number of cycles at greater amplitude before cracking, adhered to the steel bar in numerous places. The control sample broke away from the steel, retaining in the concrete a perfect impression of the steel bar.

A second experiment was designed to test the applicability of latex modified concrete to new construction for an earthquake-prone area. A cylinder of reinforced concrete was prepared, identical to the two tested previously. The additive was CEI-P at 8% by weight of the portland cement. The steel was cleaned in an acid solution and dipped in a solution of

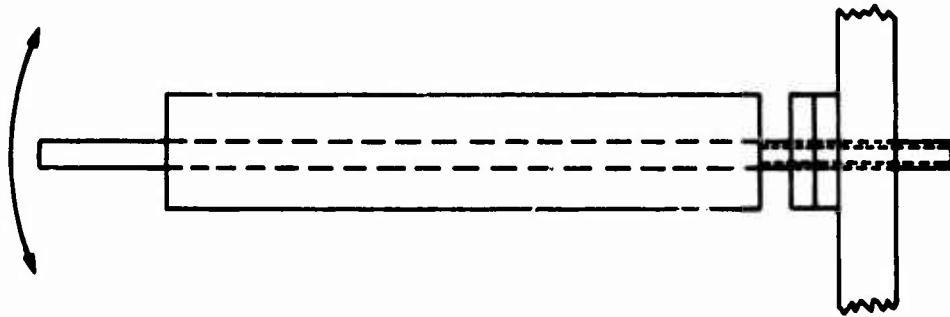


Figure 17. Flexure Testing of Reinforced Concrete. Test set-up for flexure of standard reinforced concrete, polymer-impregnated concrete, and latex-modified concrete. The concrete cylinder is 2.0 inches in diameter by 12.0 inches long; the steel bar is 0.5 inch in diameter.

1% silane and 99% cutting oil. The cured cylinder was flexed in the same manner as the previous tests; it did not crack or separate under loadings to which the impregnated sample had been exposed. While these tests were not of a quantitative nature, they nonetheless indicate the improvements possible if materials other than standard concrete are used.

Other applications of the concrete-polymer results include soil erosion control, soil stabilization for artillery bases, and construction of emergency facilities such as roads, runways, and fortifications in sandy regions. All of these were achieved using a two-component system to form a urea rubber binder; cure times are variable from 2 minutes to several hours. Several DOD activities have expressed interest in this phase of the program.

## SECTION VIII

### CONCLUSIONS

The tests conducted on various concrete-polymer systems have demonstrated several potential improvements in structural concrete. Three different systems have been evaluated, two for new construction and one for strengthening existing facilities.

For new construction latex modified concrete offers new possibilities in design where flexibility, impact resistance, and projectile damage are to be considered. The greatest advantage for LMC is its reduction of cratering almost to zero, and its ease of fabrication with existing equipment. The prospect of anti-spall and anti-fragmentation concrete is especially promising for this class of materials.

Polymer concrete will be most useful as an overlay material to be used in protecting existing structures. The relatively low cost of styrene-polyester resins combine with terminal ballistic response to offer a material capable of stopping and even reversing the motion of incoming projectiles.

Polymer impregnation will find its greatest application in strengthening of existing structures where it is desirable to reduce cratering and spall damage, and to improve resistance to additional impacts in the same location.

Several applications are foreseen in which the three systems will give the designer or engineer greater flexibility in choosing material for new construction, upgrading structures to building code, and repair of cracked or cratered roads and runways. While these materials are not likely to revolutionize the concrete industry, they do hold out the possibility of finding solutions to problems which are at present dealt with only on an interim basis.

## APPENDIX

### LATEX EMULSIONS

A large number of latex emulsions have been formulated for use as adhesive bases as well as for inclusion in mortar and concrete mixes. These are detailed in the following list, which should be regarded as neither exhaustive in scope, nor as recommending any particular manufacturer or product line.

<u>Latex</u>	<u>Manufacturer</u>	<u>Comments</u>
2544-56	Air Products and Chemicals	Vinyl Chloride
Geon 652	B. F. Goodrich	Vinyl Acrylic
Geon 660	B. F. Goodrich	Vinyl
Geon 2570	B. F. Goodrich	Vinyl Pyridine
Hylar 450	B. F. Goodrich	Acrylic
Polytex 668	Celanese Resins	
Latex 233	Dow Chemical	Styrene-Butadiene
Latex 460	Dow Chemical	
Latex 464	Dow Chemical	
Latex 18-538	Dow Chemical	
XZ-8-5080	Dow Chemical	Silane Modified SBR
777B	Dow Chemical	
Rhoplex	Rohm and Hass	Acrylic